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RESEARCH ARTICLE

Effectiveness of different types of block ramps for fish upstream movement

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Abstract Rivers are worldwide highly fragmented due to human impacts. This fragmentation has a negative effect on fish movement and dispersal. Many artificial barriers such as river bed sills and small weirs are nowadays replaced by block ramps in order to reestablish longitudinal connectivity for fish in rivers and streams. We studied the upstream passage of several fish species on different types of block ramps with slopes between 3.6 and 13.4 %. We conducted translocation experiments in the field based on mark-recapture and on the use of PIT-tags. Temporal movement patterns were observed by an instream antenna. Hydraulic and morphological characteristics of block ramps were measured and compared with fish passage efficiency. Our results clearly showed that upstream passage efficiency differs between fish species, size classes and block ramps. We observed that brown trout (*Salmo trutta fario*) performed better than bullhead (*Cottus gobio*) and several cyprinid species on the same block ramps. Passage efficiency of brown trout and chub (*Leuciscus cephalus*) was size-selective, with small-sized individuals being less successful. For brown trout, size-selectivity became more relevant with increasing slope of ramp. We conclude that block ramps with slopes of >5 % are ineffective for the small-sized cyprinid species and that vertical drops within step-pool ramps can hinder successful upstream passage of bullhead.

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Introduction

The fragmentation of the longitudinal river corridor by weirs, dams, hydropower facilities and culverts represents a major global human impact on running waters (Jungwirth 1998). In Switzerland, the extensive straightening of lowland rivers has led to a long-term increase in channel incision, which was usually counteracted by building river bed sills (Lange 2007). As a consequence, especially small rivers and streams are nowadays highly fragmented. Approximately 101,000 anthropogenic barriers with a minimal height of 0.5 m have been assessed within the Swiss river network of 65,000 km, resulting in a mean distance between barriers of 650 m (Zeh Weissmann et al. 2009).

In river systems, connectivity between downstream and upstream habitats is essential for short-term movements of fish within home ranges and directional, periodic long-distance migration. Fish usually migrate in alternating cycles between feeding, spawning and wintering habitat during different life-history stages over distances that may vary from a few metres to thousands of kilometres (Northcote 1998). Barrier-free confluences into main rivers are important linkages and provide access to spawning sites and refuges. It has been shown that dams, weirs and even small obstacles often constitute significant migration barriers to fish (Ovidio and Philippart 2002) and hence, intercept longitudinal connectivity.

The consequences of fragmentation for fish are severe. Artificial barriers can cause a loss of suitable spawning habitat in headwaters where accessibility is blocked (Sheer

and Steel 2006). Particularly, long-distance migrants such as salmon (*Salmo salar*) are susceptible to fragmentation. Thus, migration barriers triggered the loss of all diadromous species and populations in Switzerland, except the European eel *Anguilla anguilla*. Even instream structures of low height such as river bed drops of 0.2 m can represent a major threat to small-sized species like bullhead (*Cottus gobio*) or spirlin (*Alburnoides bipunctatus*) because they can separate populations (Bless 1990; Breitenstein and Kirchhofer 1999; Utzinger et al. 1998). The disruption of the longitudinal continuum can cause abrupt changes in fish communities and reduce species richness in the above-weir sites to less than half of the original richness (Peter 1998). Furthermore, it has been shown that fragmentation of the riverine system by dams has effects on the genetic composition of fish populations and leads to the loss of genetic diversity in the above-dam sites (Yamamoto et al. 2004).

The restoration of longitudinal connectivity has become a major goal in river rehabilitation. In recent years, many migration barriers such as weirs and bed-stabilizing drop structures have been removed in Switzerland and have been replaced under notable costs by block ramps, also called rock ramps, fish ramps or bottom ramps (DVWK 1996). Block ramps span the entire stream or river width and are built of boulders. They stabilize the river bed and prevent channel erosion. Since block ramps are supposed to allow for fish upstream movement and, hence, reestablish connectivity, their construction has become a popular as well as a promising approach in river engineering and management. Block ramps differ by their bed material as well as by their size and arrangement of boulders. The two main types of common block ramps consist of the classical, uniform ramp with closely embedded boulders (Type block carpet) and of the dispersed ramp (Type block clusters) that can be either structured (e.g. by rocky sills) or unstructured (Lange 2007; Tamagni et al. 2010). Roughness condition of river bed and slope are important factors that influence hydraulics and energy dissipation on block ramps (Pagliara and Chiavaccini 2006). Other characteristics of block ramps include water depth, current velocity, water temperature as well as length of ramp. A laboratory study showed that uniform block ramps can rarely satisfy the hydraulic criteria for fish migration, whereas structured block ramps are more efficient (Studer and Schleiss 2011). Fish passage can become critical with increasing discharge and steep slopes. Like in fishways, where successful upstream movement can be highly species-selective according to their design and hydraulic regime (Knaepkens et al. 2006), fish ideally benefit from repeated resting pools that reduce long reaches of strong current. There are significant differences in fish swimming capacities between species and life-stages. Since, particularly, juveniles and non-salmonids exhibit weak swimming capabilities, some hydraulic conditions—especially high velocities and critical water depths—could become problematic on block ramps. As there still is a lack of knowledge about the suitability of block ramps to benefit fish passage, the assessment of the efficiency of fish passage on block ramps is crucial.

Here, we study the upstream movement of several fish species on different types of block ramps in Switzerland. We focus on field experiments that investigate short-distance movement behavior and temporal movement patterns. We perform translocation experiments based on mark-recapture and on the use of PIT-tags. The goal of the present study was to gain information about the success of fish upstream movement on block ramps and to identify potential barrier effects for different species and size classes. We hypothesize that fish species exhibiting pronounced swimming capacities will pass steep block ramps more likely than species exhibiting weaker swimming capacities. We complement our analyses by measuring hydraulic and morphological characteristics of the block ramps. Our results may provide helpful tools for ecological evaluation of future engineering measures that effectively restore longitudinal connectivity in river networks.

Materials and methods

Block ramp characteristics

We chose eight block ramps situated in seven running waters in Central and Northern Switzerland (Table 1; Fig. 1). We classified their construction type and measured the following morphologic and hydraulic parameters: slope, length, wetted width, water depths and flow velocity. Measuring points for the latter three parameters were either regularly distributed on iterative transects within the sill-pool structure along the block ramps or situated within a grid of 1 × 0.5–1 m. We used an electro-magnetic flowmeter (Flow-Mate 2000, Marsh-McBirney) to determine flow velocity at 0.6 × water-depth and a gauge to measure water levels and bed topographies. If there was an obvious overfall at the measuring point, we determined the water level difference. We additionally measured the minimal water level difference at the sills of ramp ST because several sills caused overfalls that spanned the entire stream width and potentially posed a barrier to fish. Last, we roughly defined the granulometry of the building material of each block ramp by sizing 10 randomly selected boulders.

Translocation experiments

We based our experiments on the concept of homing behavior of fishes, which describes the tendency of fish to

Table 1 Details of the eight block ramps studied in Central and Northern Switzerland

Ramp-label	Name of the river/stream	Fish zone (Huet 1959)	Constructional subtype	Method applied	Slope (%)	Length (m)	Vertical height[a] (m)	Mean wetted width (m; SD)	Mean water depth (m; SD)	Mean flow velocity (m/s; SD)	Maximum flow velocity (m/s)
WY1	Wyna	Lower trout zone	Block carpet	Mark-recapture	13.4	13	1.7	6.0 (0.6)	0.18 (0.18)	0.54 (0.52)	1.95
WY2	Wyna	Lower trout zone	Unstructured	Mark-recapture	7.7	17	1.3	5.7 (1.0)	0.27 (0.18)	0.25 (0.32)	1.44
OF	Oftringen	Lower trout zone	Block carpet	PIT-tag logging, recapture	9.4	16	1.6	2.5 (0.4)	0.20 (0.12)	0.23 (0.24)	0.92
SI	Sissle	Lower trout zone	Structured by transversal sills	Mark-recapture	3.6	41	1.4	11.0 (1.5)	0.26 (0.14)	0.27 (0.25)	0.98
ST	Staffelegg	Lower trout zone	Structured by transversal sills	Mark-recapture	6.1	39	2.4	4.2 (0.4)	0.20 (0.11)	0.28 (0.26)	1.03
KA	Kaegiswil	Lower trout zone	Unstructured	PIT-tag logging	11.4	4	0.5	2.3 (0.6)	0.20 (0.05)	0.74 (0.45)	1.50
SU	Suhre	Grayling zone	Structured by transversal sills	Mark-recapture	5.2	40	2.1	14.0 (1.4)	n.d.	n.d.	0.70[b]
GL	Glatt	Grayling zone	Block carpet	Mark-recapture	8.9	14	1.2	14.8 (1.0)	n.d.	n.d.	3.12[b]

n.d. not determined due to exceedingly high flow velocities

[a] In reference to water surface

[b] Maximal velocity refers only to measurement at the margin of the block ramp

swim back to their home site after translocation. Armstrong and Herbert (1997) observed that experimentally displaced brown trout rapidly headed in both up- and downstream directions to the area from which they were captured. The same behavior has been described for other species, e.g. juvenile salmon, minnow (*Phoxinus phoxinus*), longear sunfish (*Lepomis megalotis*) or river blackfish (*Gadopsis marmoratus*) (Gerking 1959; Kennedy and Pitcher 1975; Huntingford et al. 1998; Khan et al. 2004). These homing movements occurred at distances of a few meters to 3.5 km. Hence, we assumed that the recaptured proportion of individuals, which we translocated, was an appropriate estimator of the passage efficiency of the block ramp investigated.

We conducted our translocation experiments at eight block ramps, two of which (SU, GL) were situated within the grayling zone and the other six (WY1, WY2, OF, SI, ST, KA) within the lower trout zone (Huet 1959). We included the grayling zone in our study because it is characterized by a broad diversity of cyprinids. In all experiments, fish were sampled by electro-fishing (electroshocker EFKO, 8 kW, 150–300/300–600 V) within a stretch of 50–200 m length located directly upstream of the block ramp. The captured fish were kept in oxygenated water tanks and were anaesthetized with clove oil before handling (Hänseler AG, Herisau, Switzerland; 0.5 ml diluted in 9.5 ml alcohol added to 20 l water). We determined the fish species, measured their total body length (±1 mm) and marked individuals subcutaneously with blue dye (Alcian Blue, Fluka, Buchs). When fish had recovered from handling, they were transferred downstream to the bottom of the block ramp and released back into the river at high densities in order to trigger active dispersal. We then gave the fish a time interval of 7–34 days to migrate back to their home sites, before we re-sampled the identical river stretches above the block ramps with electro-fishing. The recaptured individuals were carefully checked for color-marks. To test for consecutive upstream movements, translocation experiments were replicated up to three times by applying color-marks at different parts of the body to discriminate each run.

To study individual temporal movement patterns in more detail, we supplied all fish at two block ramps OF and KA with half-duplex passive integrated transponders (PIT-tag; 23 mm × 3.9 mm, 0.6 g, Texas Instruments, Dallas). We injected PIT-tags into the peritoneal cavity with a hypodermic needle on individuals with a body length >100 mm. To detect PIT-tagged fish, we installed a radio frequency identification (RFID) system and placed an in-stream low-frequency antenna at the upstream edges of both block ramps. We constructed the antenna with three loops of litz wire that were spanned in a single string over the stream resulting in an antenna width of approximately 3 m. The antenna was tuned to resonate at the frequency of 134.2 kHz and was connected to a RFID data-logger

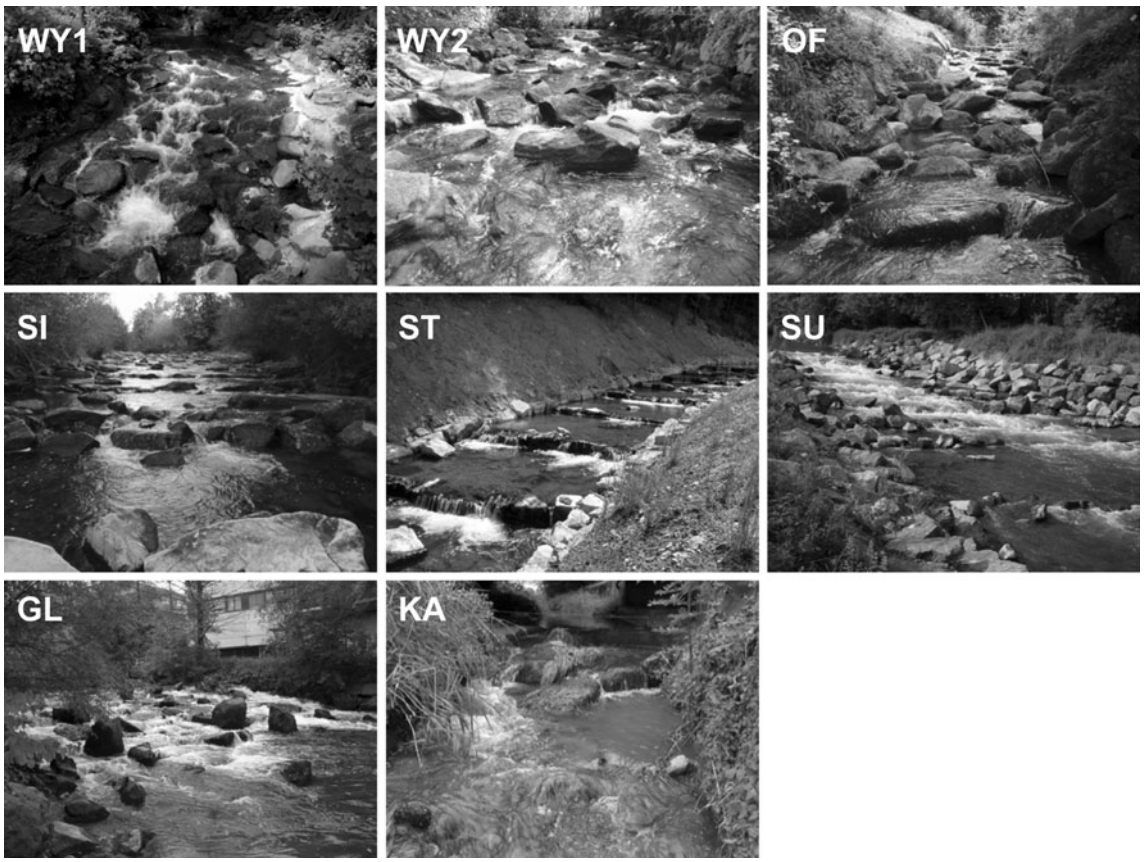

Fig. 1 Photographs taken during the field study of the block ramps WY1, WY2, OF, SI, ST, SU, GL and KA studied in Central and Northern Switzerland. See Table 1 for details

(Oregon RFID, Portland). Two interconnected batteries supplied the system with power of 18 V DC. The data-logger recorded exact date, time and individual PIT-tag identity numbers of fish passing the loop-antenna. To control for the operational efficiency of the data-logging system, we performed a recapture survey (as described above) at block ramp OF at the end of the experiment and compared logged data to the actual recapture data.

Field investigations for both block ramp characterization and translocation experiments were carried out during summer/fall (July–November) 2008 and spring (May–June) 2009.

Data analysis

We calculated mean water levels and mean flow velocities of five systematically measured block ramps (WY1, WY2, OF, SI, ST). On two occasions (SU and GL), strong water current allowed measuring only at marginal zones of the block ramps (0.3 m apart from river banks).

We calculated passage efficiency (i.e. the proportion of total fish moved) of each block ramp by dividing the number of recaptured or logged migrants by the total number of color-marked or tagged individuals. We derived passage efficiencies for different fish species and size-classes. The effects of fish body length and ramp slope on passage success were statistically analyzed on block ramps WY1, WY2, OF and SI for brown trout, the most abundant species. For this, we used two different logistic regression models (SPSS Statistics 17.0). We omitted block ramps from the grayling zone, SU and GL, from the logistic regression analysis because of a comparatively small sample size of brown trout on these ramps. Both logistic regression models (1) and (2) included as categorical outcome, i.e. dependent variable, the individual recapture above the block ramps (yes/no). Model (1) included fish body size as a single predictor (independent variable). Model (2) included fish body size, slope of block ramp as well as their interaction as predictors (stepwise forward method).

Results

Block ramp characteristics

Of the eight block ramps investigated, bed slopes ranged from 3.6 to 13.4 %, with WY1 and KA having the steepest

slopes (Table 1; Fig. 1). Note that block ramps have different characteristics. Block ramps with slopes below 6.5 % were more than twice as long as steeper ramps. Usually, maximum flow velocity increased with slope, except for the outlier ramp OF (Table 1). Water levels were not critical for fish under discharge conditions during the experiment. The most critical velocity for fish was recorded at the ramp GL having a maximal flow velocity of 3.12 m/s on marginal zones. Comparatively, the presence of calm marginal areas turned out to be relevant on ramp SU because boulders on beds formed zones with a maxima of 0.7 m/s. Mean flow velocity of other block ramps was distributed between 0.23 and 0.28 m/s (Table 1) with maximal velocity of 0.9–1.5 m/s, but was higher on the steepest block ramp WY1, which had a mean velocity of 0.54 m/s and a maximum of 1.95 m/s. Occasionally, we recorded a minimum water level difference at vertical drops of 0.1–0.23 m between sills at block ramp ST.

Upstream passage efficiency

Table 2 provides an overview of all species captured, as well as the number of marked or tagged individuals at each block ramp. We marked more than 3,000 individual fish belonging to 16 different fish species, with body lengths ranging from 35 to 540 mm. Passage efficiencies are listed in Table 2 expressed as either recapture or detection rates for each block ramp and fish species.

Lower trout zone

We caught 666 brown trout at block ramps WY1, WY2, OF and SI with a mean body length of 144 mm. The corresponding passage efficiencies of these four block ramps are depicted in Table 2. Note that the second recapture rates were slightly lower than the rates of the first recapture. Our results clearly show major and consistent differences in passage efficiency between size classes within species and block ramps. Figure 2 depicts the strong difference between the two size classes <200 mm and ≥ 200 mm of brown trout on each of these four block ramps. The logistic regression model (1), which compared recaptures of OF, WY1, WY2 and SI altogether, revealed that body size as a single factor makes a significant contribution to predicting the passage rate of brown trout (Table 3). With increasing body length, the odds for a brown trout of getting recaptured upstream of the ramp increased by a factor 1.02 [95 % CI (1.016; 1.023)]. The stepwise forward logistic regression model (2) revealed a significant interaction between the factors slope and fish size (Table 3), whereas slope did not fulfill the significance criterion and was excluded from the model. The model (2) showed that the difference between small- und large-sized brown trout in passing the block ramp increased with the steepness of the ramp slope. This means the influence of fish size on passage success was more prominent on a steep than on a smooth ramp. Surprisingly, total passage efficiency independent of size-class for brown trout was highest on the steepest block ramp WY1 and lowest on the block ramp SI, which had the smallest slope. Furthermore, it is noteworthy that a relatively high proportion of twice-translocated brown trout passed the block ramps a second time (72.4 % on block ramp WY1, 47.2 % on WY2 and 50.0 % on SI, respectively, relative to the total of double-marked individuals).

In contrast to brown trout, we encountered an extremely poor upstream passage efficiency of bullheads on block ramps WY1, WY2 and ST (Table 2). Of the total 477 marked bullheads, none was recaptured after 7 or 14 days upstream of block ramps WY1 and WY2, nor after 11 days, 20 days or 34 days upstream of block ramp ST. Block ramp ST consists of a step-pool-step system with 13 sills in total. Several marked individuals had moved up to pool numbers 1–5 during the first (7.6 %; $N = 17$), second (7.7 %; $N = 24$) and third (3.2 %; $N = 10$) recapture. Nevertheless, none crossed the sixth sill, which had a height of 15 cm under the conditions that were met during the experiment.

At block ramp SI, we encountered a large minnow population. Of the total 1,104 marked and translocated minnows, however, none were recaptured after 7 or 14 days, respectively.

Grayling zone

At block ramp KA, passage efficiency of large sized chub (≥ 200 mm) was relatively high: almost a third of this size class had passed the ramp after 4.5 days (Table 2).

The two study sites SU and GL were characterized by high, yet different species diversities. At block ramp SU, the highest efficiency was seen by the size class of large brown trout (Table 2). Sample sizes were small for small-sized fish like gudgeon, grayling, minnow, dace and spirlin and we did not recapture any individuals of these species after 6 or 29 days. Sample sizes of chub and barbel at block ramp SU were quite high, yet passage efficiency was surprisingly low (Table 2). We did not observe any consecutive upstream passages at ramp SU for neither of these species. At block ramp GL, upstream passage in reasonable numbers was restricted to large-sized chub and brown trout. A strikingly unsuccessful upstream passage was revealed for gudgeon, barbel, roach and small-sized chub (<200 mm) after 22 days.

Temporal movement patterns

The PIT-tag reading-system operated during 16 days at block ramp OF and during 4.5 days at block ramp KA with

Table 2 Fish recapture rates upstream of ramps WY1, WY2, OF, SI, ST, SU, GL and KA for the 16 species encountered

Fish species	Size class	WY1				WY2				OF			SI				ST					KA		SU				GL	
		N_1	N_{tot}	RC_1	RC_2	N_1	N_{tot}	RC_1	RC_2	N_{tot}	DT	RC	N_1	N_{tot}	RC_1	RC_2	N_1	N_{tot}	RC_1	RC_2	RC_3	N_{tot}	DT	N_1	N_{tot}	RC_1	RC_2	N_{tot}	RC
Brown trout *Salmo trutta fario*	<200 mm	140	206	33.6	33.5	141	218	26.2	18.3	80	35.0	25.0	33	48	9.1	6.3	–	–	–	–	–	–	–	23	52	4.3	1.9	9	11.1
	≥200 mm	35	47	82.9	80.9	28	44	57.1	47.7	9	77.8	44.4	12	14	41.7	35.7	–	–	–	–	–	–	–	6	13	33.3	23.1	3	100
Bullhead *Cottus gobio*		78	107	0	0	46	57	0	0	–	–	–	–	–	–	–	223	313	0	0	0	–	–	–	–	–	–	–	–
Chub *Leuciscus cephalus*	<200 mm	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2	0	46	57	8.7	0	67	0
	≥200 mm	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	24	29.2	58	90	6.9	3.3	7	14.3
Barbel *Barbus barbus*		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	56	105	7.1	1.9	74	2.7
Gudgeon *Gobio gobio*		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	11	12	0	0	225	1.3
Grayling *Thymallus thymallus*		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6	10	0	0	–	–
Minnow *Phoxinus phoxinus*		–	–	–	–	–	–	–	–	–	–	–	472	1,104	0	0	–	–	–	–	–	–	–	9	11	0	0	–	–
Dace *Leuciscus leuciscus*		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	5	5	0	0	–	–
Spirlin *Albumoides bipunctatus*		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	22	23	0	0	–	–
Roach *Rutilus rutilus*		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	18	0
Tench *Tinca tinca*		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2	0
Stone loach *Barbatula barbatula*		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	0
Pike *Esox lucius*		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	0	–	–	–	–	1	0
Eel *Anguilla anguilla*		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	0
Perch *Perca fluviatilis*		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	100	–	–	–	–	4	0
Sunfish *Lepomis gibbosus*		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6	0

Recapture rates for brown trout and chub are listed for two size classes separately (≥200, <200 mm)

RC_X Xth recapture event, *DT* detection rate by PIT-tag reader, N_1 number of marked and translocated individuals before 1st recapture, N_{tot} cumulative number of marked and translocated individuals before 2nd (or 3rd) recapture

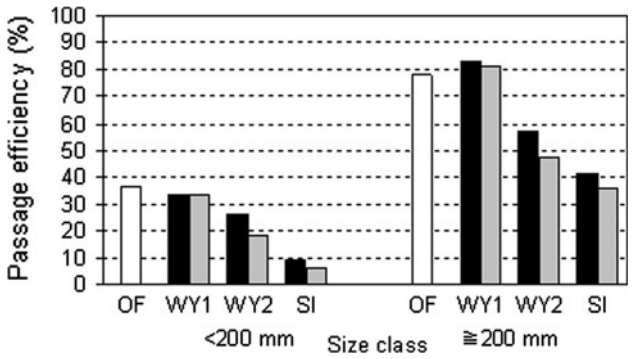

Fig. 2 Passage efficiency according to Table 2 of brown trout (*Salmo trutta fario*) for small-sized and large-sized individuals. Passage efficiency at ramps WY1, WY2 and SI corresponds to 1st and 2nd recapture rate. Passage efficiency of block ramp OF is pooled data from recaptured as well as reader-detected individuals. *Black bar* 1st recapture rate. *Gray bar* 2nd recapture rate. *White bar* recapture pooled with detecting rate

short interruptions to accommodate battery changes and data transfer. At block ramp KA, 26.9 % of chub had passed after 4.5 days, whereas in total 40.5 % of trout had passed after 16 days (pooled with recapture data) at block ramp OF.

Upstream movements of chub were concentrated in the evening, whereas the movement activity of trout started in the afternoon and ceased in the morning, reaching a peak before midnight (Fig. 3). On block ramp OF, two peaks of movement activity of brown trout became evident during the course of observation. The first peak consisted in a clear preference for upstream movement during the first night and day after translocation (40 % of movements; Fig. 4). The second peak (28.6 % of movements) followed during and after a heavy rainfall that caused an increase in discharge and turbidity combined with a drop in water temperature.

Comparing passage efficiencies of mark-recapture and reader-system at block ramp OF, we found that the control catch indicated an efficiency of brown trout of 26.9 %, with only one individual not being detected by the antenna. In contrast, efficiency according to reader-system was higher and accounted for 39.3 % of the brown trout. Additionally, the advantage of the reader-system was the recording of four individuals, which had passed the ramp successfully but moved downstream again and were recaptured at the ramp bottom.

Discussion

The main objective of the present study was to assess the effectiveness of block ramps for fish upstream movement. We studied brown trout, bullhead and several species of cyprinids and found that upstream passage differs between species. Brown trout performed better than bullhead and any cyprinid species on the same block ramps. Successful passage in reasonable numbers for the nonsalmonid, comparatively small-bodied species bullhead, minnow and gudgeon was not observed. Our results clearly show that upstream passage efficiency differs between size classes within species and block ramps. Passage efficiency of brown trout and chub is size-selective, with small-sized individuals being far less successful. For brown trout, this effect becomes more important with increasing slope of ramp. However, we do not know whether the differences between small- and large-sized individuals are caused by efficiency per se or by differing motivation. Furthermore, we showed that environmental factors can influence behavior and that with elevated discharge, upstream swimming activity of brown trout is stimulated. Generally, swimming and leaping performances as well as physiological condition of fish limit their passage efficiency across obstacles. The distance a fish can swim in upstream direction with constant effort declines with increasing water velocity. Velocity barriers that exceed the physiological or behavioral capabilities of fishes define the distributional limits of their populations (Haro et al. 2004). Agreeing with our study, large-sized trout cope well with slopes of 26, 16.5 and 10 % on relatively short obstacles of 2.98, 5.13 and 8 m in length, respectively (Ovidio et al. 2007). However, the repeated recovery in resting pools is necessary for fish in order to prevent total exhaustion

Table 3 Logistic regression models (1) and (2) calculated for passage of brown trout on block ramps WY1, WY2, OF and SI

Model	Variables	B	SE	Wald	df	Sig.	Exp (B)	95 % CI for Exp (B)	
								Lower	Upper
Model (1)	Fish size	0.019	0.002	112.716	1	0.000	1.019	1.016	1.023
	Constant	−3.782	0.303	156.273	1	0.000	0.023		
Model (2)	Fish size	0.008	0.002	11.407	1	0.001	1.008	1.003	1.013
	Fish size × slope	0.001	0.000	36.639	1	0.000	1.001	1.001	1.002
	Constant	−3.950	0.317	155.377	1	0.000	0.019		

Model (1): Cox & Snell R^2 0.202, Nagelkerke R^2 0.287. Model (2): Cox & Snell R^2 0.249, Nagelkerke R^2 0.353

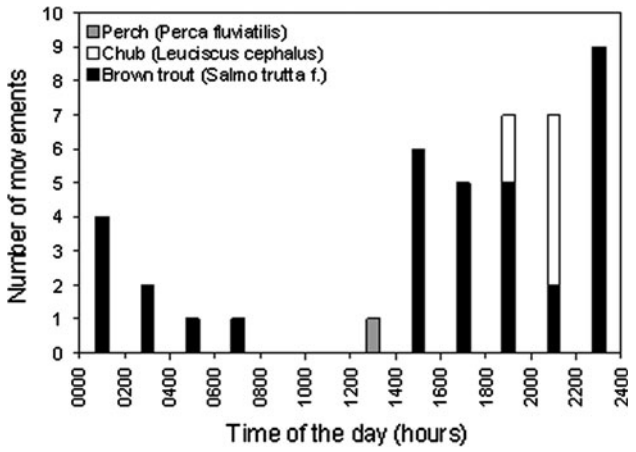

Fig. 3 Temporal movement activity expressed as number of upstream movements obtained from PIT-tagged individuals on ramps OF and KA related to time of the day. Pooled number of upstream movements over a period of 16 days at ramp OF and of 4.5 days at ramp KA (ramp KA: perch N = 1, chub N = 7; ramp OF: brown trout N = 35; translocated fish were released in each case between 1100–1200 hours)

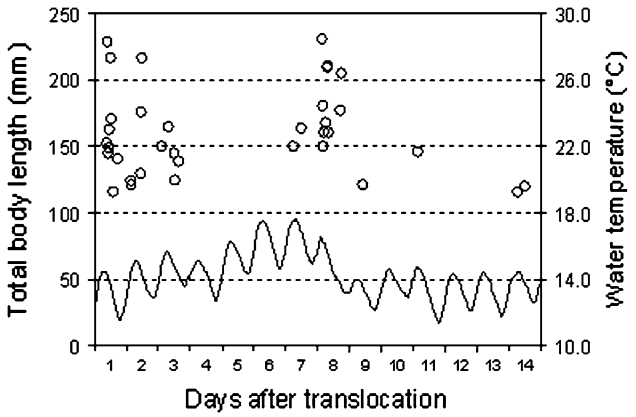

Fig. 4 Temporal progress of upstream movement of PIT-tagged brown trout on ramp OF. *White circles* indicate individuals in respect of their body size. The *curve below* depicts the water temperature. Start of temporal axis at 12 a.m. after release of fish. Interruption of detection on day number 5 due to battery failure. Increase in discharge on the evening of day 7

because burst swimming is anaerobic and can only be maintained for a few seconds. A number of studies have shown that physical swimming capabilities are influenced by water temperature (Hammer 1995). Holthe et al. (2005) document leaping heights of 0.18–0.27 m for minnow depending on size-class at water temperatures of 14.0–16.5 °C, but recorded no leaping behavior at low temperatures outside of spawning season. We conclude that swimming performance of small species is often not sufficient to cope with flow velocities measured on the block ramps we studied.

In European minnow, a general motivation for active homing under laboratory conditions has been reported (Kennedy and Pitcher 1975). However, the cause for the missing passage of minnows across the block ramp SI in our study is unclear. Whereas adult brown trout are usually highly mobile and also migrate outside the spawning period (Ovidio and Philippart 2002), this may not be the case for the minnow. Even though the low passage rate of the migratory species barbel in our data is likewise surprising, it nevertheless corresponds to previous findings that showed that obstacles systematically blocked migration of barbel, whereas trout could clear obstacles with slopes of more than 30 % (Ovidio and Philippart 2002). Unsuccessful passage of roach has been described in a different study, in which upstream movement of roach was limited by physical barriers as they do not frequently clear obstacles even during reproduction migration (Geeraerts et al. 2007). Passage failure of downstream transferred bullhead has also been observed at a fish pass, most likely due to excessive water velocities (Knaepkens et al. 2006). Like our findings at step-pool-step ramp ST, there was a general tendency of a few individuals to move upstream several pools, but they never fully ascended. High bidirectional mobility for a closely related *Cottus* species has been demonstrated in a continuous stream during a 1-year period using longitudinal home ranges of up to 435 m (Ovidio et al. 2009). Hence, we suppose that bullhead had failed to pass the block ramps during our experiments due to limiting swimming and leaping capabilities rather than to a lack in motivation for micro-homing. We conclude that sills of 0.15 m hinder upstream movement of bullhead upon structured block ramps.

Evidence on species-specific responses to habitat fragmentation by weirs is provided by Blanchet et al. (2010) comparing chub, dace, gudgeon and minnow. Contradictory to our results, their genetic study showed that the smallest-sized species minnow was the least affected by fragmentation, and the authors therefore suggest that dispersal behavior rather than dispersal ability per se could explain species sensitivity to weirs. However, we note that differences in effective population size could also explain these results if smaller species had larger effective population sizes. Recent findings indicate that chub as well as brown trout are likely to perform micro-homing after translocation and that with increasing body length of trout the probability of micro-homing increases (A. Peter, unpublished data). It is possible that individual behavior such as timing of migration and motivation for micro-homing could have influenced our experiments. Under the assumption that all species that we studied tend to return to the capture-site, our data reveal a strong lack of connectivity across block ramps. However, given the uncertainties regarding homing behavior in cyprinid species, our results

should not be considered as a definite indicator of effectiveness for cyprinids. We stress the need for comparative studies on micro-homing behavior outside spawning season, notably for small-sized species.

Comparing antenna-detection with mark-recapture, we cannot exclude an underestimation of actual upstream movements in the mark-recapture experiments. Hence, the antenna-detection of PIT-tagged fish is a qualified method to evaluate the effectiveness of block ramps and out-performs the conventional method of mark-recapture to detect movement patterns. Our temporal observation showed that upstream passage of brown trout and chub happens within a short time period. Contrary to a study on sea lamprey (Quintella et al. 2004), we found fish to be particularly active not only during darkness, but also in the afternoon. The response of fish to movement during a heavy rainfall suggests the close dependence on discharge conditions or turbidity. Likewise, clearance of obstacles and fishways in an upstream direction can be triggered under elevated discharge and within a certain range of temperature (Laine et al. 2002; Ovidio and Philippart 2002), whereas diurnal movement of the cyprinid species *Leuciscus idus* was found to be influenced by turbidity per se independent of discharge (Kulíšková et al. 2009). Our temporal data on brown trout indicates that the testing of block ramps during summer should be avoided because physical stress due to elevated water temperatures may affect upstream passage. If fish are unable to pass an obstacle, they wait downstream, sometimes several weeks, for environmental conditions to improve (Ovidio and Philippart 2002), which consequentially delays the arrival at spawning grounds. The hydraulic measurements, which we took during low flow condition on each block ramp, only revealed excessive current velocities of ramps in the grayling zone. Nevertheless, these measurements reflect the snap-shot conditions and it is recommended that passage for fish should be assured during approximately 300 days per year (Friedrich et al. 2005).

We conclude that steep block ramps with a slope >6 % can reestablish longitudinal connectivity and fish migration corridors in the trout zone only for large-sized brown trout. Although passage rates for brown trout indicate less success for juveniles, large-sized individuals pass these block ramps successfully. The comparably long, step-pool-like block ramp comes with low current velocities and has the advantage of providing resting pools. However, there is a risk at low discharge for having vertical drops of sills that fish can only clear by leaping. In view of our results and of previous findings of Utzinger et al. (1998), such drops have a serious negative effect on small-sized species with low leaping potential like bullhead. Block ramps should be constructed in such a way that sills do not feature vertical drops. Our results indicate that block ramps with slopes of >5 % in the grayling zone are insufficient for the small-sized cyprinid species. Block ramps within the grayling zone can be improved by rip-rap structures along the shoreline that provide calm areas underneath boulders.

Our study is a first attempt to assess the effectiveness of block ramps for different fish species. We point out that the results are subject to potential constraints caused by the behavioral experiments. We emphasize the necessity of monitoring block ramps during the pre- and post-construction phase to determine species as well as genetic diversity down- and upstream of the obstacle and to quantify effects of the block ramp construction on fish assemblage structure. If block ramps were more effective at interconnecting downstream with upstream fish habitat they could considerably contribute to goals of river restoration and conservation. However, more research is needed to improve the design of block ramps to achieve this.

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